SINGLE-MODE CAVITY-QED OF A RAMAN INTERACTION

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Abstract

We consider a single Rydberg atom having two degenerate levels interacting with the radiation field in a single-mode ideal cavity. The transition between the levels is carried out by a Λ-type degenerate two-photon process via a third level far away from single-photon resonance. At the start of interaction, the atom is considered to be in a coherent superposition of its two levels and the field in a coherent state. We study the dynamics of the atomic as well as the field states. The squeezing in the quadratures of atomic states can reach up to 100%. The cavity field evolves to a statistical mixture of two coherent fields with the phase difference between them decided by the interaction time. Analysis of entropies of the atom and the field shows that the two systems are dis-entangled periodically in certain cases.

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1. Introduction:

The high-Q cavity quantum electrodynamics (QED) has been extensively investigated as this simple system can be a source of nonclassical fields in addition to answering some fundamental questions in quantum mechanics. The dynamics involves a single atom with its two or three Rydberg levels interacting with the cavity field. In the case of a two-level atomic system, it is the Jaynes-Cummings model (JC) [1] and the revival in the atomic population in its evolution, a singature of quantum mechanics, has been experimentally investigated [2]. These revivals are, in general, Gaussian in shape which gets broader in successive appearances in time and finally overlap with one another giving rise to a chaotic evolution. The three-level atomic system involving a two-photon process on the other hand gives rise to compact revivals which are regularly placed and are also more distinct for a relatively longer time compared to the case in a two-level system [3-6]. A two-photon process concerns transition from one level to another via an intermediate level involving a single photon in each transition. If this intermediate level is removed far from one-photon resonance, then the three-level system can be reduced to an effective two-level system, the validity of which has been discussed in detail in refs. 5 and 6. This process in a high-Q cavity, the so-called two-photon micromaser, has been experimentally demonstrated [7]. Various nonclassical properties, such as squeezing [8], has also been theoretically predicted in the two-photon case. The quadrature squeezing [8a] in a degenerate two-photon process [9,10] where the involved two photons are of same frequency can go upto 75 percent. The two-mode squeezing [8b] takes place in the case of nondegenerate two-photon process [5,6,11] where the involved two photons are of different frequencies. Quadrature squeezing [8a] has also been indicated in the nondegenerate case [12]. In addition to various squeezing in the radiation field, the atomic states can also be squeezed in the two-photon dynamics [13]. In a typical cavity QED experiment, atom in a selected state enter the cavity at such a rate that at most one atom is allowed to interact with

the field for a fixed duration. Hence, the two-photon cavity-QED can be a useful source for obtaining atoms in squeezed states. In ref. 13, the atom initially in one of the two degenerate levels connected by a Raman-type interaction with a single mode of the cavity field was considered. The study showed that squeezing in a particular quadrature of the atomic states can only be possible. However, this situation can be changed if the atom is in a coherent superposition of two levels at the start of the interaction. Atomic squeezing can be possible in either quadrature for wider values of involved parameters and, also, the squeezing can be enhanced. It is also interesting to find how the atomic coherence effect the evolution of the cavity field. The present paper addresses to these problems and, also, examines other aspects of the dynamics such as entropy which is a measure of atom-field correlation. It is interesting to find if the atom and the field are dis-entangled during the evolution. In section 2, we present the model with its solution. Sections 3 and 4 examine atomic and field dynamics respectively. The enropies of the atom and the field are discussed in section 5. We conclude the paper in section 6.

2. The model and its solutions:

We consider two degenerate Rydberg levels i and f of an atom interacting with the single mode of frequency ω of an ideal cavity (Q=∞). The transition between i and f takes place by a two-photon process via an intermediate level removed far away from one-photon resonance. This can be represented by an effective Hamiltonian, in a frame rotating at $\omega a^\dagger a$,

$$H_{eff} = g a^\dagger a (S^+ + S^-) \tag{1}$$

where $a(a^\dagger)$ is the annihilation(creation) operator for the radiation field. S^+ and S^- are Pauli pseudospin operators for the atomic levels $|i>$ and $|f>$. g is the coupling constant for the two-photon interaction. Effective Hamiltonian of the type in eq. (1) has been widely used in literature [3,4,13]. The range of validity of such Hamiltonians has been

closely investigated in refs 5 and 6. It is not the aim in this paper to re-examine the range of validity of eq. (1). However, we shall restrict ourselves in a region where eq. (1) is usually a true representation of the interaction.

The time evolution of the atom-field wave function $|\psi>$ is given by

$$|\psi(t)>=\exp(-iH_{eff})|\psi(0)> \tag{2}$$

where $|\psi(0)>=|\psi(0)>_{atom}\otimes|\psi(0)>_{field}$ is the initial condition. For the atom, we assume

$$|\psi(0)>_{atom}=\cos(Z/2)|i>+\exp(iW)\sin(Z/2)|f> \tag{3}$$

where Z represents the degree of superposition between $|i>$ and $|f>$ and W is the phase of this superposition. The cavity field at t=0 is assumed to be in a coherent superposition of photon number states $|n>$ with complex amplitude α given by

$$|\psi(0)>_{field}=\exp(-|\alpha|^2/2)\sum_{n=0}^{\infty}\frac{\alpha^n}{\sqrt{n!}}|n> . \tag{4}$$

The dressed states of the system, given by $H_{int}|\psi_n^{\pm}>=\pm gn|\psi_n^{\pm}>$ with

$$|\psi_n^{\pm}>=[|i,n>\pm|f,n>]/\sqrt{2}$$

have been seen to be convenient for simplifying the eq. (2). A straight forward calculation gives

$$\begin{aligned}|\psi(t)> &= \exp(-|\alpha|^2/2)\sum_{n=0}^{\infty}\frac{\alpha^n}{\sqrt{n!}}[(\cos(Z/2)\cos gnt - ie^{iW}\sin(Z/2)\sin gnt)|i,n> \\ &\quad +(e^{iW}\sin(Z/2)\cos gnt - i\cos(Z/2)\sin gnt)|f,n>]\end{aligned} \tag{5}$$

Equation (5) represents combined atom-field system at any time during the evolution. From the density operator $\rho_{atom-field}=|\psi(t)><\psi(t)|$, we can obtain atomic as well as field statistics by appropriate tracing.

3. Atomic statistics:

The atomic probabilities $\rho_{i,i}(t)$ and $\rho_{f,f}(t)$ for the states $|i>$ and $|f>$ respectively have interesting properties. We have

$$\rho_{i,i}(t) = \sum_{n=0}^{\infty} | < n|A_i(t) > |^2 \tag{6}$$

and

$$\rho_{f,f}(t) = \sum_{n=0}^{\infty} | < n|A_f(t) > |^2 \tag{7}$$

where

$$\begin{aligned} |A_i(t) > \quad &= \quad \frac{1}{2}\exp(-|\alpha|^2/2)\sum_{n=0}^{\infty}\frac{\alpha^n}{\sqrt{n!}}[e^{ignt}\{\cos(Z/2) - e^{iW}\sin(Z/2)\} \\ &+e^{-ignt}\{\cos(Z/2) + e^{iW}\sin(Z/2)\}]|n > \end{aligned} \tag{8}$$

and

$$\begin{aligned} |A_f(t) > \quad &= \quad \frac{1}{2}\exp(-|\alpha|^2/2)\sum_{n=0}^{\infty}\frac{\alpha^n}{\sqrt{n!}}[e^{ignt}\{e^{iW}\sin(Z/2) - \cos(Z/2)\} \\ &+e^{-ignt}\{\cos(Z/2) + e^{iW}\sin(Z/2)\}]|n > . \end{aligned} \tag{9}$$

Examining $|A_i >$ and $|A_f(t) >$, we find that for $gt = \pi/2$ and $Z = W = 0$

$$|A_i >= [|i\alpha > +| - i\alpha >]/2 \tag{10}$$

and

$$|A_f >= -[|i\alpha > -| - i\alpha >]/2 \tag{11}$$

are, apart from a normalizasion factor, that for even and odd coherent states respectively [14, 15]. $|A_i >$ and $|A_f >$ interchange properties for $Z = \pi$. Whereas for $gt = Z = W = \pi/2$, we get

$$|A_i(t) >= \frac{e^{-i\pi/4}}{2}[|i\alpha > +e^{i\pi/2}| - i\alpha >] \tag{12}$$

and

$$|A_f(t) >= -\frac{e^{-i\pi/4}}{2}[|i\alpha > -e^{i\pi/2}| - i\alpha >] \tag{13}$$

which are that for a Yurke-Stoler coherent state [16]. In general, we have, for $W = \pi/2$,

$$|A_i(t)>= \frac{1}{2}e^{-iZ/2}[|\alpha e^{igt}> + e^{iZ}|\alpha e^{-igt}>] \tag{14}$$

and

$$|A_f(t)>= -\frac{1}{2}e^{-iZ/2}[|\alpha e^{igt}> - e^{iZ}|\alpha e^{-igt}>], \tag{15}$$

the phase difference between the superpositions being decided by the interaction time. Thus we see that the quantities $| < n|A_i(t) > |^2$ and $| < n|A_f > |^2$ as function of n display characteristics of the distribution functions for the cat-like states for the field. However, the summations in eqs. (6) and (7) give atomic state probabilities $\rho_{i,i}$ and $\rho_{f,f}$ respectively. On the other hand, such summations are the usual normalization conditions if the distribution functions were for the radiation field. This is consistent with the fact that the states in eqs. (10)-(15) are like various cat-like states apart from a normalization factor. Similar characteristics have been discussed in the ref. 4.

These are nonclssical properties involved in the atomis state probabilities. In addition, the quadratures of the atomic states show squeezing [8a]. We define

$$S^x = [S^+ + S^-]/2 \tag{16}$$

and

$$S^y = [S^+ - S^-]/2i \tag{17}$$

which are related by

$$[S^x, S^y] = iS^z. \tag{18}$$

Hence the variances $(\Delta S^x)^2$ and $(\Delta S^y)^2$ in S^x and S^y respectively obey the uncertainty relation

$$(\Delta S^x)^2(\Delta S^y)^2 \geq \frac{1}{4}| < S^z > |^2 \tag{19}$$

where $S^z = (|i >< i| - |f >< f|)/2$ is the population difference operator between the levels $|i >$ and $|f >$. $(\Delta S^x)^2$ or $(\Delta S^y)^2 < | < S^z > |/2$ indicates squeezing in that

quadrature. The percentage of squeezing is an useful parameter in the estimation of noise reduction and is given by

$$P = 100[1 - 2(\Delta S^i)^2/| < S^z > |]\% \tag{20}$$

where $i = x$ or y. As the present analysis involves a single-atom dynamics, we have $< S^+ S^+ > = < S^- S^- > = 0$ and hence we have

$$(\Delta S^x)^2 = (1 - \sin^2 Z \cos^2 W)/4 \tag{21}$$

and

$$(\Delta S^y)^2 = [1 - \{\sin \xi(t) \cos Z - \cos \xi(t) \sin W \sin Z\}^2 \exp(-4|\alpha|^2 \sin^2 gt)]/4 \tag{22}$$

where

$$\xi = |\alpha|^2 \sin(2gt). \tag{22a}$$

The population difference is given by

$$< S^z > = \frac{1}{2}[\cos \xi(t) \cos Z + \sin \xi(t) \sin W \sin Z] \exp(-2|\alpha|^2 \sin^2 gt). \tag{23}$$

We immediately see that, for $Z = 0$ or $= \pi$ indicating that the atom is in the state $|i>$ or $|f>$ at $t = o$, there is no squeezing in the X-component as $(\Delta S^x)^2 = 1/4$ with $| < S^z > | \leq 1/2$. The possibilities of squeezing in the Y-component has been discussed in the ref. (13). However, the situation can be changed if the interaction starts with the atom in a superposition of its two states which indeed produces squeezing in the X-component. This is a key result in the paper.

Now we look into few interesting cases in which squeezing is possible. For $W = 0$ and $gt = m\pi$ with $m = 1, 2, 3, ...$, $< S^+ > = \frac{1}{2} \sin Z$ and, hence, there is no squeezing in Y-component. The condition for squeezing in S^x becomes $\cos^2 Z < |\cos Z|$ which is clearly satisfied for $Z \neq n\pi/2$ with $n = 0, 1, 2, ...$ Similar situation arises for $W = 0$ and

$gt = (2m+1)\pi/2$, $m = 0, 1, 2, ...$ where the condition for squeezing in the X-component takes the form

$$\cos^2 Z < |\cos Z| \exp(-2|\alpha|^2)$$

which further reduces to $n\pi - \eta < Z < n\pi + \eta$ where $\eta = \arccos[\exp(-2|\alpha|^2)]$ with $n = 0, 1, 2....$ There are a few cases in which time evolution of squeezing takes oscillatory patterns, an example of which is displayed in fig. (1) around $Z = \pi/2$ and $W = 0$. For a fixed $Z = \pi/2$ ans small W such that $e^{iW} = 1 + iW$, we can write

$$< S^+ >= [1 - iW \cos\xi(t) \exp(-2|\alpha|^2 \sin^2 gt)]/2 \tag{24}$$

and

$$| < S^z > | = \exp(-2|\alpha|^2 \sin^2 gt)| \sin\xi(t)|W/2 \tag{25}$$

This gives us a condition of squeezing in X-component as

$$gt \neq \frac{1}{2} \arcsin(n\pi/|\alpha|^2) \tag{26}$$

where $n = 0, 1, 2, ...$ and in such a situation the squeezing is nearly 100% according to eq. (20). $n = 0$ indicates that there is no squeezing in the initial condition of the atom. Further, from eq. (24), we have

$$(\Delta S^y)^2 = (1 - W^2 \cos^2 \xi(t) \exp(-4|\alpha|^2 sin^2 gt)]/4 \cong 1$$

and hence there is no squeezing in Y-component in this situation. Apart from these special cases, numerical studies show squeezing in either quadrature.

3. Field statistics:

The field density operator is given by

$$\rho_f = |A_i(t) >< A_i(t)| + |A_f(t) >< A_f(t)| \tag{27}$$

where $|A_i(t)>$ and $|A_f(t)>$ are given by eqs. (8) and (9). Using eqs. (14) and (15), we find that the coherent field $|\alpha>$ at $t=0$ evolves to

$$\rho_f = \frac{1}{2}[|\alpha e^{igt} >< \alpha e^{igt}| + |\alpha e^{-igt} >< \alpha e^{-igt}|] \tag{28}$$

which is a statistical mixture of coherent states $|\alpha e^{igt}>$ and $|\alpha e^{-igt}>$ [14]. We see that the phase difference between the two states is decided by the interaction time. This result is for $W=\pi/2$ in the initial condition in eq. (3). The field also shows similar characteristics for other values of W. The photon distribution fuction for the field, obtained from eq. (27)

$$P_n =< n|\rho_f|n >= e^{-|\alpha|^2}\frac{(|\alpha|^2)^n}{n!} \tag{29}$$

is that for a coherent field. The Wigner function [17] for ρ_f, derived by using the method in refs. [15,18], have the form

$$\begin{aligned} P_w(x,y) &= \frac{2}{\pi}[(1+\cos W\sin Z)\exp\{-2(x+k_1x_1-k_2y_1)^2 \\ &\quad -2(y+k_1y_1+k_2x_1)^2\}+(1-\cos W\sin Z) \\ &\quad \exp\{-2(x+k_1x_1+k_2y_1)^2-2(y+k_1y_1-k_2x_1)^2\}] \end{aligned} \tag{30}$$

where $k_1=\cos gt$, $k_2=\sin gt$ and $\alpha=x_1+iy_1$ is the complex amplitude of the coherent field at $t=0$. We see that the function $P_w(x,y)$ is always positive and is twin-peaked in the complex space with each peak being Gaussian in shape. This is consistent with the fact that the radiation field, in general, a statical mixture of two coherent fields [14]. It has been seen that a field with these characteristics does not possess squeezing properties in its quadratures which is also the case in the present investigation. Other properties of such fields have been analysed in ref. (14).

5. Entropy:

Study of entropy (for atom/field) as a system dynamical parameter and as a measure of

field-atom correlation has been given for the JC model [19,20] and some of its generalized forms [21-23]. The Boltzmann-Gibbs entropy is defined by (scaled by Boltzmann's constant)

$$S = -Tr(\rho \ln \rho) \tag{31}$$

where ρ is the system density operator. The entropy S_f for the field, represented by ρ_f in eq. (27), is given by

$$S_f = -(\pi_1 \ln \pi_1 + \pi_2 \ln \pi_2) \tag{32}$$

where $\pi_{1,2}$ are the eigenvalues of ρ_f [20],

$$\pi_{1,2} = \lambda_{11} \pm \exp^{\mp\delta} |\lambda_{12}| \tag{33}$$

ans also

$$\pi_{1,2} = \lambda_{22} \pm \exp^{\pm\delta} |\lambda_{12}|, \tag{33a}$$

with

$$\lambda_{11} =< A_i|A_i >= 1/2+ < S^z >,$$

$$\lambda_{22} =< A_f|A_f >= 1/2- < S^z >,$$

$$\sinh \delta =< S^z > /|\lambda_{12}|,$$

$$|\lambda_{12}| = | < A_i|A_f > | = \sqrt{R^2 + I^2}/2,$$

$$R = \sin Z \cos W,$$

$$I = \exp(-2|\alpha|^2 \sin^2 gt)[\sin Z \sin W \cos \xi(t) - \cos Z \sin \xi(t)]$$

and $\xi(t)$ and $< S^z >$ are given by eqs.(22a) and (23). Similarly, for the present two-level atomic structure, its entropy S_a is given by [19],

$$S_a = -(\alpha_1 \ln \alpha_1 + \alpha_2 \ln \alpha_2) \tag{34}$$

where

$$\alpha_{1,2} = \frac{1 \pm 2\sqrt{< S^z >^2 + |\lambda_{12}|^2}}{2}. \tag{34a}$$

It may be easily verified that $S_a = S_f$ [20] which is due to the absence of damping processes. Henceforth, we use the symbol S for either S_a or S_f. From the above analytical expression for S we note the following:

(i) For $gt = n\pi$ and arbitrary W , $e^{\delta} = (1 + \cos Z)/\sin Z$ and hence $S = 0$. This emplies that the field and the atom are decorrelated (dis-entangled) periodically.

(ii) For strong fields ($|\alpha|^2 \to \infty$), $\pi_{1,2} = \alpha_{1,2} = (1 \pm R)/2$ and hence S is independent of time.

The graph for $S(t)$ for $W = Z = 0$ and $|\alpha|^2 = 5$ is presented in fig. (2). For $Z = \pi/4$ and $W = 0$ the graph of $S(t)$ is similar is shape but the horizontal peak value in different. Within a semiclassical approximation that ignores the field fluctuations the effective Hamiltonian in eq. (1) reduces to

$$H_{sc} = 2g|\alpha|^2 S^x \tag{35}$$

The equation of motion for the Bloch vector $\mathbf{S}(t) = (S^x, S^y, S^z)$ is of the form

$$\dot{\mathbf{S}}(t) = \mathbf{\Omega}(t) \times \mathbf{S}(t) \tag{36}$$

with $\mathbf{\Omega}(t) = (2g|\alpha|^2, 0, 0) = \mathbf{\Omega}(0)$ being constant in time (note that eqs.(35, 36) are special case of the corresponding equations in ref. [23] for the resonant two-photon JC model when the Stark shift is neglected). The time evolution of the Bloch vector with the atom initially in an atomic coherent state, eq. (3), shows that:

(i) For the cases $(W = 0, \pi/2, \pi; Z = 0), (W = Z = \pi/2)$ and $(W = \pi/2, Z = \pi/4)$ the vector $\mathbf{S}(0)$ is orthogonal to $\mathbf{\Omega}(0)$ which means that the amplitude of the Bloch vector $\mathbf{S}(t)$ is maximum and hence the entropy S is maximum. The numerical results show that $S(t)$ has maximum value $S_{max} = 0.658$ in its periodic evolution.

(ii) For the cases $W = 0(\pi)$ and $Z = \pi/2$, the vector $\mathbf{S}(0)$ is parallel(anti-parallel) to the vector $\mathbf{\Omega}(0)$ which means that the amplitude of the Bloch vector $\mathbf{S}(t)$ goes to zero and hence $S(t)$ has a reduced maximum value. In fact, one can show analytically from the eq.

(33) that for $W = 0, \pi$ and $Z = \pi/2$, $\pi_{1,2} = 1, 0$ and hence $S(t) = 0$.

(iii) For the cases $W = 0, \pi$ and $Z = \pi/4$, $S(0)$ is neither perpendicular nor parallel to $\Omega(0)$ which indicates a decrease in S_{max}. Numerical results show that $S_{max} = 0.41$ which is less that its value in the case (i).

6. Conclusion:

We have analysed a degenerate Raman process involving two degenerate Rydberg energy levels of an atom interacting with the radiation field in the single mode of a cavity with $Q = \infty$. The initial condition for the cavity field is assumed to be coherent. The atomic statistics display a rich variety of nonclassical properties if the atom is in a coherent superposition of the two levels at the start of the interaction. The squeezing is seen to be possible in either quadrature for a wide range of numerical values of the parameters involved. Interesting special cases are, if the atom is in a state

$$|\psi(0) >_{atom} = \frac{1}{\sqrt{2}}[|i > +(1 + iW)|f >] \tag{37}$$

with no squeezing in its quadratures initially, the X-quadrature gets nearly 100% squeezed during the evolution except at singular atom-field interaction time given by the condition in eq. (26). On the other hand, if the atom is in one of the two states at $t = 0$, then squeezing appears in the Y-quadrature. Regarding the field statistics, we notice that the initial coherent state $|\alpha >$ evolves to a statistical mixture of two coherent states.

Entropy evolution was also examined for various initial conditions and also discussed within the semiclassical Bloch equations. The equality of field and atomic entropies is due to the absence of any dissipative processes. For short interaction times, the ideal cavity approximation ($Q = \infty$) has been seen to be a good approximation [24]. But, for arbitrary time, the following master equation needs to be solved,

$$\begin{aligned}\dot{\rho} = -i[H_{eff}, \rho] - \kappa(1 + \bar{n}_{th})(a^\dagger a\rho - 2a^\dagger \rho a + \rho a^\dagger a) \\ -\kappa\bar{n}_{th}(aa^\dagger \rho - 2a\rho a^\dagger + \rho aa^\dagger)\end{aligned} \tag{38}$$

where H_{eff} is given by eq. (1), $\kappa = \omega/2Q$ is the cavity dissipation constant and $\bar{n}_{th}$ is the average black-body photons in the cavity. It is expected that the field entropy will evolve independently towards its maximum and/or steady-state value and the atomic entropy will be effected by the cavity dissipation processes (cf.[25]. Results of these investigations for the present model and other damped cavity-QED systems will be presented later.

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Figure Captions:

Figure 1: Percentage of squeezing in S^x for $W = 0$ and for $Z = 1.50$ (full), $= 1.53$ (broken) and $= 1.56$ (dotted).

Figure 2: Entropy for the field or atom for $Z = W = 0$ and $|\alpha|^2 = 5.0$.